A Fusion Method for Estimating the Walking Direction of Smartwatch Users

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Abstract

Accurately estimating the walking direction of smartwatch users is critical for applications such as exercise trajectory analysis. This study introduces a novel approach that fuses estimation direction from inertial sensors and GPS. Inertial sensors provide stable estimates as they are unaffected by environmental conditions, but their accuracy can be impacted by sensor performance and user motions, such as hand swinging. GPS, in contrast, offers higher accuracy than inertial sensors under favorable signal conditions. To leverage the strengths of both sensors, the proposed method employs an information-weighted consensus filter, integrating direction estimates and error covariances. Experimental results demonstrate that the fusion approach reduces estimation errors compared to individual sensors.

Keywords: smartwatch, inertial sensor, walking direction, pedestrian inertial navigation

1. Introduction

Pedestrian localization systems using wearable devices are a field of active research. While the Global Navigation Satellite System (GNSS) is highly effective for localizing pedestrians outdoors, it is hindered by environmental limitations [1]. In urban environments, GNSS signals often experience multipath effects or signal attenuation, leading to reduced accuracy. To address this, map-matching methods have been proposed, but these require highly detailed maps and face challenges in predicting a pedestrian's walking trajectory.

Inertial sensors are employed to mitigate GNSS's environmental limitations. These sensors are already integrated into wearable devices, eliminating the need for additional infrastructure. Pedestrian Dead Reckoning (PDR) is a method that leverages inertial sensors to continuously estimate a pedestrian's position by calculating step length and walking direction [2]. However, when devices such as smartwatches are used, aligning the device's orientation with the pedestrian's walking direction becomes challenging.

Approaches utilizing Attitude and Heading Reference Systems (AHRS) to estimate walking direction often assume alignment between the device and the pedestrian's walking direction, which limits their general applicability. Other studies employ Principal Component Analysis (PCA) methods to extract dominant components from acceleration patterns during walking [3]. These methods provide useful results when the pedestrian swings their arm while walking. However, due to the limitations of inertial sensors, estimating the absolute walking direction remains challenging. Additionally, since these methods rely on the statistical characteristics of acceleration patterns, their accuracy may decrease depending on a pedestrian's walking style or arm-swinging habits.

In this paper, a walking direction estimation algorithm that integrates inertial sensors and GNSS is proposed. For inertial sensor-based walking direction estimation, a previously developed PCA-based algorithm is utilized [4]. For GNSS-based direction estimation, Recursive Least Squares (RLS) is applied to estimate the pedestrian's walking direction from positional data. The directions estimated from the two sensors are fused using the Information-Weighted Consensus Filter (ICF), which considers the error covariance of each sensor's estimation.

The structure of this paper is as follows. Section II introduces walking direction estimation methods and details the proposed algorithm. Section III presents experimental results demonstrating the performance of the proposed algorithm. Finally, Section IV provides conclusions and discusses future work.

2. Fusion method for walking direction

The proposed method estimates a user's walking direction and error covariance by integrating inertial sensors and GNSS data. First, a previously developed inertial sensor-based walking direction estimation method is employed, which extracts principal components from the acceleration distribution over several steps to estimate the user's direction. The core equation for the PCA-based method is shown below:

$$\hat{\theta}_{PCA} = \arg\max_{\theta} \left(\sum_{i=1}^{M} \left(\boldsymbol{\beta} \cdot \boldsymbol{\alpha}_i^n \right)^2 \right) \qquad (1)$$

Here, $\hat{\theta}$ represents the walking direction, $\boldsymbol{\alpha}_i^n$ denotes the accumulated acceleration vector in the navigation frame over several steps, $\boldsymbol{\beta}$ represents a specific parameter (denoted as $\boldsymbol{\beta} = [\cos\theta \ \sin\theta]^{\mathrm{T}}$), and M is the number of steps. The estimation accuracy is influenced by the number of steps.

Since PCA does not inherently provide an index for estimation error, an error index for the proposed method is introduced. This index uses the eigenvalues of the two principal components derived during PCA to represent the degree of error. The error index can be expressed as the ratio of the two eigenvalues:

$$P_{PCA} = \tilde{\theta}^2, \ \tilde{\theta} = \tan^{-1}\left(\frac{\lambda_2}{\lambda_1} \right) \qquad (2)$$

where λ_1 and λ_2 are the eigenvalues of the first and second principal components, respectively. A large λ_1 and a small λ_2 indicate a sharp distribution with minimal estimation error. Conversely, a large λ_2 suggests a broader acceleration distribution, making it challenging to estimate a clear direction. Figure 1 illustrates the concept of the error index.

For GNSS-based walking direction estimation, positional data are utilized, and the Recursive Least Squares (RLS) algorithm is applied, which provides computational efficiency based on the recursive formulation [5]. The estimated walking direction is expressed as follows:

$$\hat{x}_i = \hat{x}_{i-1} + K_i (y_i - \varphi_i \hat{x}_{i-1}), \qquad (3)$$

$$K_i = \frac{P_{i-1}\varphi_i^T}{1 + \varphi_i P_{i-1} \varphi_i^T} \qquad (4)$$

$$P_i = \frac{12}{\Delta t^2 N (N^2 - 1)} \qquad (5)$$

$$K_i = \frac{P_{i-1}\varphi_i^T}{1 + \varphi_i P_{i-1} \varphi_i^T} \qquad (6)$$

where y represents the GNSS positional measurements, $x = [v^T, p^T]^{\mathrm{T}}$ denotes the state variables, and $\varphi = [(i-1)\Delta t, 1]^T$ is the regressor. To calculate the error covariance, we leverage the relationship between the Horizontal Dilution of Precision (HDOP) of the GNSS and the estimated velocity.

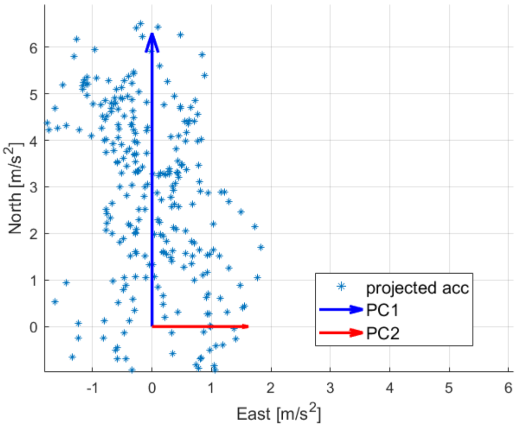

Fig. 1. Estimated walking direction error of PCA-based method.

$$P_{GNSS} = P_i \cdot \frac{\sigma_{HDOP}^2}{2 \| \hat{v} \|^2} \qquad (7)$$

GNSS-based direction estimation exhibits high accuracy during prolonged linear movements due to the clear tendency in the walking direction. However, during turns, the regression model becomes inconsistent, requiring calculations based only on short-term measurements.

Using the two methods described above, the walking direction and error covariance are calculated. The proposed method combines these using the Information-Weighted Consensus Filter (ICF) [6]. ICF is a widely used technique in sensor fusion, particularly effective when the sensors have varying reliability. It adjusts the weights of erroneous data to minimize their impact on the fusion results. The final direction calculated by the proposed method is expressed as:

$$\hat{\theta}_{fusion}^{k} = \hat{\theta}_{fusion}^{k-1} + \varepsilon W' \sum_{i \in \{PCA, GNSS\}} (\hat{\theta}_i - \hat{\theta}_{fusion}^{k-1}) \qquad (8)$$

$$W_{fusion}^{k} = W_{fusion}^{k-1} + \varepsilon \sum_{i \in \{PCA, GNSS\}} (W_i - W_{fusion}^{k-1}) \qquad (9)$$

$$W' = \frac{W_{fusion}^{0}}{W_{PCA} + W_{GNSS}} \qquad (10)$$

where $W = P^{-1}$ represents the information matrix. This approach allows us to obtain a combined movement direction estimation by considering the contributions and error covariances of the individual sensors.

The ICF combines the two estimated directions through an iterative process, as outlined in equations (8) and (9). This process refines the fusion result by iteratively adjusting the weights of the estimated directions based on their respective error covariances. The iterative nature of ICF ensures that the final estimation accounts for the reliability of each input while minimizing the influence of erroneous data. This robust fusion mechanism is crucial for achieving high accuracy in walking direction estimation under varying conditions.

3. Experiment

To evaluate the performance of the proposed method, outdoor experiments were conducted. The participant wore a Samsung Galaxy Watch 5 on their left wrist, and data from the watch's inertial sensors and GNSS measurements were utilized to validate the estimation performance. For ground truth walking direction, the MTi-680G sensor from Xsens was employed. This sensor provides highly accurate positional information using RTK, which was differentiated to calculate the walking direction.

The experiments were conducted in an urban environment within an apartment complex, where the GNSS signal quality was poor, with HDOP values ranging from 6 to 12 meters. The participant walked for approximately 15 minutes, following a trajectory shaped like the number 9.

Figure 2 illustrates the estimated walking directions over the entire experiment. The black line represents the reference direction, the blue line corresponds to the PCA-based estimation, the red line represents the GNSS-based estimation, and the green line shows the result of the proposed fusion method. At around the 400-second mark, the participant waited at a crosswalk, resulting in no change in the estimated walking directions. Overall, it was observed that the GNSS-based walking direction exhibited large errors, while the PCA-based and fusion-based results demonstrated smaller errors.

Table 1. RMSE of estimated walking direction.

	PCA	GNSS	Fusion
RMSE [deg]	11.32	20.42	**10.98**

Table 1 presents the RMSE values for walking direction estimation using each method. The proposed method achieved lower errors compared to the individual sensor-based methods. Given the challenging GNSS conditions of the experimental site, the GNSS-based method showed significant errors, whereas the PCA-based method had smaller errors. Consequently, the fusion results of the proposed method were more influenced by the PCA-based estimation.

Figure 3 shows a zoomed-in view of the estimation errors during a straight-line walking segment. In this scenario, the errors of the PCA-based and GNSS-based results were similar, but the proposed method exhibited relatively smaller errors. This highlights the utility of the GNSS-based method in straight-line situations and provides justification for combining the two sensor-based methods in the proposed approach.

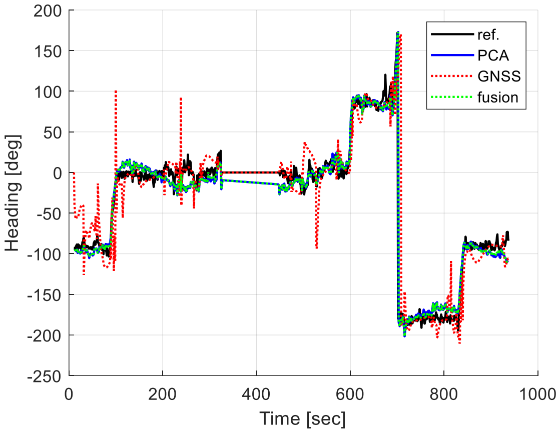

Fig. 2. Estimated walking direction results.

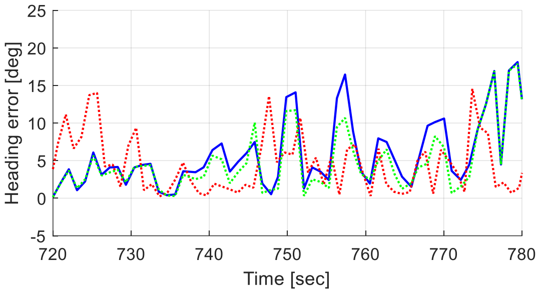

Fig. 3. Estimated walking direction results (straight trajectory).

4. Conclusion

In this study, a walking direction estimation algorithm was proposed, integrating inertial sensors and GNSS data using the ICF. The algorithm successfully addressed the limitations of individual sensor-based methods by leveraging the strengths of both PCA-based inertial sensor and GNSS measurements. Experimental results demonstrated that the proposed method achieved lower errors compared to standalone sensor approaches, particularly in urban environments with challenging GNSS conditions. Furthermore, the analysis highlighted the robustness of the fusion method in varying scenarios, such as straight-line and complex trajectories. These findings suggest that the proposed approach is effective for improving walking direction estimation in wearable devices, paving the way for more reliable pedestrian navigation systems.

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Authors Introduction

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